CONTROL OF A WATERJET PROPELLED VESSEL

The present application claims priority to US Provisional Patent Application 60/525,888, filed December 1, 2003, the entirety of which is incorporated by reference herein.

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BACKGROUND

The present invention relates to the control of a water jet propelled vessel. Such waterjet propelled vessels are known and can range in size from small personal watercraft to boats of up

10   to 75 feet in length, or vessels of even larger size.

A waterjet-powered vessel is moved through the water by accelerating a stream of water through a nozzle, thereby moving the vessel in reaction to the accelerated stream of water. The nozzle can be fixed to the rear of the vessel and aimed to produce lateral forces on the vessel which are used to steer the vessel. The waterjet is either engaged and pumping water or not

15   engaged and not pumping water. Multiple waterjets/nozzles can also be used. The nozzle at the rear of the vessel is also usually equipped with a reversing bucket which, when activated, redirects some or all of the nozzle flow to produce a reversed component of thrust on the vessel. A waterjet thruster can also be positioned in or near the bow of the vessel with its axis essentially perpendicular to the vessel's bow-stern axis to produce lateral forces at the bow of the vessel.

20   Combined, the rear nozzle, reversing bucket and bow thruster can be used to simultaneously maneuver the watercraft in any desired direction or heading.

The vessel can be equipped with a multi-axis joystick that allows the operator to simultaneously control the nozzle angle, reverse bucket position, and bow thrusters. Forward

and aft movement of the joystick activates the reverse bucket. Sideways movement of the joystick activates the bow thruster, and nozzle angle is controlled by a twisting movement of the joystick.

U.S. Patent No. 6,234,100 to Fadeley, dated May 22, 2001, discloses a Stick Control System For Waterjet Boats and U.S. Patent No. 6,230,642 to McKenney, dated May 15, 2001 discloses an Autopilot Based Steering And Maneuvering System For Boats. U.S. Patent Application No. 2003/0054707 to Morvillo, dated March 20, 2003, discloses an Integral Reversing And Trim Deflector And Control Mechanism and U.S. Patent Application No. 2003/0079668 to Morvillo, dated May 1, 2003 discloses a Method And Apparatus For Controlling A Waterjet Driven Marine Vessel. These two patents and two patent applications are incorporated by reference herein.

Despite the degree of control offered by these maneuvering and steering control systems, there remains a need for a control system that improves control algorithms to provide a more predictable control system that is more intuitive to operate.

SUMMARY OF THE INVENTION

The present invention includes several embodiments for controlling a watercraft. A first embodiment includes acquiring a desired heading of the watercraft, acquiring an actual heading of the watercraft at time T_0, calculating a heading error by comparing the desired heading with the actual heading, determining a rate of change of the heading error and determining a P gain, I gain and D gain for use in maintaining the heading of the watercraft. Then, a $PtermT_0$, $ItermT_0$, and $DtermT_0$ are determined using the following equations:

$$PtermT_0 = P * \text{Heading Error}$$

$$ItermT_0 = ItermT_{0-1} + (I * \text{Heading Error} * (T_0 - T_{0-1}))$$

$$DtermT_0 = D * \text{Rate of Change of Heading Error}$$

wherein P, I and D are the determined P gain, I gain and D gain, respectively. A value for

5   Control $OutT_0$ is then determined by summing the values for $PtermT_0$, $ItermT_0$, and $DtermT_0$ and

then an amount of deflection for a nozzle of the watercraft is determined, for altering a heading

of the watercraft, based on the value for Control $OutT_0$. The nozzle is deflected based on the

determined amount of deflection and the T_0 to T_{0+1} are reset with the steps being repeated until

the actual heading equals the desired heading.

10   A second embodiment for calculating a heading of a watercraft includes acquiring a

heading of the watercraft at a base time, acquiring a heading turn rate from an angular rate of

turn sensor of the watercraft at a later time and determining whether the acquired heading is

believed accurate at the later time. If the acquired heading is believed inaccurate, a heading of

the watercraft is calculated by adding a factor for the heading turn rate to the acquired heading

15   and the calculated heading output for control of the heading of the watercraft.

           A further embodiment for correcting a heading of a watercraft, includes measuring an

amount of error induced by the effect of at least one disturbance on at least one of x, y and z

heading data from a heading sensor, acquiring at least one of x, y and z heading data from a

heading sensor, determining whether the at least one disturbance is occurring, correcting the

20   heading data in the occurrence of a disturbance by adding a factor to the heading that offsets the

measured amount of error induced by the disturbance and outputting the corrected heading data

for control of the heading of the watercraft.

A further embodiment for controlling roll out of a watercraft includes determining whether a nozzle control apparatus is off center to alter a position of a nozzle of the watercraft and if the nozzle control apparatus is off center, setting a nozzle control command to a nozzle control apparatus command, determining whether the nozzle control apparatus has been returned to a center position, determining a heading rate for the watercraft and if the nozzle control apparatus has been returned to a center position, setting a nozzle control command to a negative of the heading rate multiplied by a constant factor predetermined for the watercraft based on operating data of the watercraft.

A further embodiment for controlling a watercraft having a rear nozzle for propulsion and a bow thruster includes, during at least one of initiation and cessation of sideways movement of the watercraft, prepositioning an angle of the rear nozzle to provide a sideways force that minimizes vessel yaw prior to the occurrence of a heading error, the prepositioned angle based on the operating characteristics of the watercraft.

A further embodiment for controlling a watercraft having a rear nozzle for propulsion and a bow thruster includes initiating a sideways movement of the watercraft by engaging the rear nozzle while delaying engagement of the bow thruster and engaging the bow thruster after a first predetermined time delay to assist in the sideways movement of the watercraft after a stern of the watercraft has gained sideways momentum from the rear nozzle, the first predetermined time delay based on the operating characteristics of the watercraft to minimize yaw of the watercraft during the sideways movement.

A further embodiment for the control of a watercraft having a magnetic sensor for determining a heading of the watercraft includes reducing the effect of electro-magnetic field interference from electrical equipment of the watercraft on the accuracy of a heading signal from

the magnetic sensor controlling use of the heading signal based on at least one of a function

mode of the watercraft and a position of a vessel movement control apparatus by at least one of:

compensating for the field interference and acquiring the heading signal only when electro-

magnetic interference is sufficiently low to prevent substantive inaccuracy of the heading data.

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BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a logic flow chart for a first embodiment of the present invention;

10   Fig. 2 is a logic flow chart for a second embodiment of the present invention;

Fig. 3 is a logic flow chart for a third embodiment of the present invention;

Fig. 4 is a logic flow chart for a fourth embodiment of the present invention;

Fig. 5 is a logic flow chart for a fifth embodiment of the present invention;

Fig. 6 is a logic flow chart for a sixth embodiment of the present invention; and

15   Fig. 7 is a logic flow chart for a seventh embodiment of the present invention.

DESCRIPTION OF THE INVENTION

The present invention includes several control methods for controlling the waterjet

20   propelled vessel. These methods can be used individually or in combination with one or more of

the other control methods to control the vessel. In the preferred embodiment, the control system

will include several or all of the various control methods.

These control methods can be incorporated in the controller that controls activation of the nozzle, reversing bucket and bow thruster of the vessel and when used, will operate as described below, and can do this taking into account operator input, vessel movement data and other collected data or desired operating parameters. In all methods, alternate thrusting devices can

5   also be used. The methods can be used with watercraft having one or more nozzle and reversing bucket sets, controllable in unison or independently.

Maintaining Heading of a Watercraft

One problem with current waterjet control systems of the type referenced above is their

10   inability to effectively maintain heading. To be more commercially viable, the control system must give the operator the feeling that he or she is in complete control of the vessel. Overshooting turns and erratic or unstable straight-line performance do not give the operator the feeling of being in control.

In one control method of the invention, the control system maintains proper vessel

15   heading at all speeds without operator intervention. To maintain the heading, the control method compares the desired heading to the actual heading and deflects the nozzle to correct the error. Regardless of vessel speed, including zero speed, the controller automatically maintains the vessel heading by simultaneously controlling all propulsors, including bow thrusters, and thrust vectoring devices such as waterjets.

20   See Fig. 1 for a logic flow chart of this control method. First, the desired heading is acquired. This can either be input into the system or captured by the system based on a heading at a specific acquisition time. Next, the actual heading is acquired at step 10. In a preferred embodiment, this is acquired from a three axis heading sensor hard-mounted to the vessel and

connected to the electronic controller. The sensor has three axes, each of which uses a magneto-inductive sensor that measures the earth's magnetic field. Because the heading sensor is hard-mounted to the vessel and the vessel is subject to pitch and roll movements from waves, the signal from the heading sensor may be adversely affected. To correct this condition, a pitch and

5   roll sensor mounted to the vessel can be used to measure pitch and roll and provide a signal indicating the pitch and roll to the controller to enable correction of the heading signal. Other types of heading sensors can also be used.

Once the actual heading is acquired, whether from a magnetic sensor or not, the heading error is calculated at step 12 by subtracting the actual heading from the desired heading. Since

10   the vessel dynamics are different depending on whether the bow thruster is active, it is then determined whether the bow thruster is active or not at step 14.

This control method controls vessel steering by means of an algorithm that utilizes the heading error (the difference between the desired heading and the actual heading) in such a way as to maintain a heading. This algorithm is comprised of the sum of three terms. One term is

15   proportional to the heading error, one term is proportional to the heading error that has accumulated over time, and the last term is proportional to the rate-of-change of the heading error. The result of this summation is used to position the steering device. Each summation term has a multiplier associated with it, which determines that terms' effect on the overall output. These multipliers are often referred to as gains. The first gain is the "P" gain. This is sometimes

20   referred to as rudder gain, since this gain controls how much of the heading error gets applied to the position of the steering device. This term causes the steering device to position itself proportional to the heading error, in the direction that corrects the heading error. The second gain is the "I" gain. This is sometimes referred to as trim, since it effectively adds an offset to the

center position of the steering device over time. This eliminates any long-term heading offset

due to wind and waves. The third gain is the "D" gain. This is sometimes referred to as counter-

rudder. This term causes the steering device to position itself proportional to the rate of turn of

the vessel, in the direction that opposes the rate of turn. Other control methods or rules can also

5   be used.

Depending on whether the bow thruster is active or not, different sets of data will be

accessed for determining "P", "I" and "D". As shown at steps 16a and 16b, "P", "I" and "D" will

differ based on the engine rpm. That is, since the amount of flow through the nozzle increases as

engine rpm increases, it is desirable to make the "P", "I" and "D" factors dependent on engine

10   rpm. While the "P", "I" and "D" factors will generally decrease as engine rpm increases, this

may not be the case in some instances, as shown for the "P" factor in step 16b. The "P", "I" and

"D" factors can also be dependent on vessel speed. For instance, in a low speed docking mode of

operation, gain values would generally be set higher to produce sufficiently correcting control of

the nozzle. At higher speeds, the gain magnitudes would be set lower since the vessel is more

15   sensitive to changes at the nozzle than at lower speeds. The different curves for each factor can

be determined through use of empirical data or through theoretical calculation and can be

modified for the dynamics of a specific vessel. The method can take into account other states of

the vessel's positioning and propulsing systems, e.g., thruster pushing port, thruster pushing

starboard, bucket position, operating mode, and operator's control interface position, all of which

20   are not shown on the logic flow chart.

At step 18, $PtermT_0$, $ItermT_0$ and $DtermT_0$ are calculated based on the "P", "I" and "D"

data selected in step 16. $PtermT_0$ is calculated by multiplying "P" by the heading error. $ItermT_0$

is calculated by adding the previous iteration/time period Iterm ($ItermT_{0-1}$) to the factor "I" times

Heading Error times $(T_0 - T_{0-1})$. $DtermT_0$ is calculated by multiplying "D" times the rate of change of the heading error (determined by comparing the current heading error with the heading error from the previous time period and dividing by $(T_0 - T_{0-1})$). Once these terms have all been calculated, they are summed together at step 20 to arrive at Control $OutT_0$, which is the signal

5   used to control the amount of deflection of the nozzle in the desired direction.

In steps 22 and 24 following step 20, the amount of nozzle deflection and the maximum rate of nozzle deflection indicated by step 20 can be limited based on engine rpm. As engine rpm increases, the effect of the deflection of the nozzle increases. Therefore, these limitations imposed at steps 22 and 24 prevent deflection of the nozzle at too large of an angle or rate of

10   change of angle that might allow the vessel to become unstable or feel unstable to the operator. The signal, whether limited or not in steps 22 and 24 is then output for the control of the nozzle at step 26.

This signal can be a direct signal to the nozzle actuator or can be used to signal another component that controls the nozzle actuator. The cycle then repeats at step 28, returning to the

15   top of the loop. In one embodiment, this cycle repeats approximately 20 times per second but this frequency can be altered as desired.

This control method allows the vessel to be maintained accurately on a desired heading without further input from the vessel operator by adjusting the deflection of the nozzle based on the data selected. It includes limiting factors that prevent heading correction from happening too

20   rapidly that the vessel becomes unstable or the passengers become uncomfortable. This method can be embodied as hardware, software or a combination of the two. It can be incorporated into an existing navigational controller for the vessel or can be a stand alone component. Other thrust vectoring devices can be used, for example, the rudder. One advantage of this method is that the

operator doesn't have to fidget with the autopilot interface to adjust sensitivity when changing

speed. Also, when tying up the vessel, the operator doesn't have to worry about the vessel

twisting in the slip. Nor does the operator have to worry about vessel twisting when activating

the bow thruster.

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Use of Angular Rate Of Turn Sensor And Heading Sensor To Calculate Heading

Another feature of the present invention is a method which uses an angular rate sensor in

conjunction with a heading sensor to calculate the current actual heading for display or for use in

vessel motion control. The heading sensor can be in the form of 1) a three-axis magnetic

10   heading sensor, occasionally referred to as a strap-down heading sensor, preferably used in

conjunction with a pitch and roll sensor as discussed above for error correction; 2) a gimbaled

type sensor; 3) a Global Positioning System and/or another type of heading sensor/system.

Many heading sensors filter their outputs such that during fast maneuvering, the sensor

output can lag behind, overshoot, and/or otherwise not reflect the actual heading of the vessel.

15   Global Positioning Systems of a moderate price range may not update rapidly enough or provide

the accuracy necessary for precise real-time vessel control. Further, the GPS system may not

receive the necessary satellite information to provide the correct data to calculate actual heading.

Thus, when the actual heading data used to calculate heading is inaccurate or missing, the current

method can compensate for this. The current method uses an angular rate of turn sensor, such as

20   a gyro type sensor, to produce a signal, used in conjunction with the data from the heading

sensor, to calculate the actual heading if it is determined that the heading data provided by the

heading sensor is not likely to be reflecting the actual heading, or between heading updates (as in

a GPS system). As an example of one implementation of this method where the signal from a heading sensor is being filtered and is not reflective of the actual heading, see Fig.2.

Therefore, until the data from the heading sensor can be trusted again as being accurate, the heading data is calculated using heading turn rate data. In the shown method, the heading is

5   acquired from the heading sensor at time T_0, step 30. In the first iteration, the Calculated HeadingT$_0$ = Heading Sensor HeadingT$_0$, step 32. The heading turn rate is then acquired from an angular rate of turn sensor at time T_{0+1}, step 34. It is then determined whether the heading turn rate is above or below a predetermined threshold at step 36. If it is below the threshold, it is assumed that the turn is not being made so fast that the data from the heading sensor is likely to

10   be inaccurate. Therefore, the heading sensor headingT$_0$ is output to whatever control method or mode needs such data at step 38, the time T_0 is reset at step 40 and a new iteration can start at step 30. If the heading turn rate is above the threshold at step 36 such that it is believed that the heading from the heading sensor may be inaccurate, a calculated heading is calculated at step 42 and the calculated heading is output to whatever control method or mode needs such data at step

15   44. Then, the time T_0 is reset at step 46 and a new iteration can start at step 34. When the heading turn rate falls below the predetermined threshold, the calculated heading portion of the loop will be left at step 38 and the process returns to the top of the flow chart, as discussed above.

A similar method can be used in a system where GPS data is being used to provide heading data. See Fig. 3. Here, the GPS data may not update sufficiently fast to provide the

20   required heading data. Therefore, between updates, the heading data is again calculated using heading turn rate data. In the shown method, the GPS heading is acquired at time T_0, step 50. This GPS heading is then output at step 52, and the Calculated HeadingT$_0$ is set to the GPS HeadingT$_0$, step 54. It is then determined whether a new GPS update has been received at time

T_{0+1}, step 56. If so, the Calculated Heading$T_{0=1}$ is set to the GPS Heading$T_{0=1}$ at step 58 and this

GPS heading is output at step 64. If no new update has been received, the heading turn rate is

acquired from an angular rate of turn sensor at time T_{0+1}, step 60. A calculated heading is

calculated at step 62 and the calculated heading is output at step 64. Then, the time T_0 is reset at

step 66, the calculated heading reset at step 68 and the process returns to step 56 to determine

whether a new GPS update is available. If not, a new iteration of the bottom loop is performed. If

so, the process leaves the bottom loop and returns to the top of the flow chart.

The heading sensor can also be vulnerable to disturbances that affect its output so that the

output does not reflect the actual heading. For instance, a magnetic heading sensor is very

sensitive to magnetic disturbances that can be caused by operation of equipment on the vessel.

Similarly, the gimbaled type sensor can be sensitive to shock or vibration of the vessel, which

can affect the accuracy of its output. The existence of such a disturbance can be determined by

measurement, such as with a vibration/shock sensor measuring an amount of vibration/shock.

The existence of a disturbance can also be assumed when one or more predetermined conditions

are met. For instance, in one embodiment, it is assumed that a disturbance is occurring when

electrical equipment is operating, thereby causing a magnetic interference with a magnetic

heading sensor. The controller can be signaled when such equipment is operating so that it can

take corrective action. This method provides a way for correcting the negative effect of the

disturbance on the heading data.

In one embodiment shown in Fig. 4, a heading is acquired at step 70 and a calculated

heading is set to be the acquired heading at step 72. It is then determined whether a disturbance

has occurred at step 74. If not, the heading acquired from the heading sensor is assumed to be

accurate and is output at step 76. The process then returns to the top of the flow chart. If a

disturbance is determined to be occurring so that a newly acquired heading is not believed to be accurate at time T_{0+1}, the heading turn rate is acquired from an angular rate of turn sensor at time T_{0+1}, step 80. A calculated heading is calculated at step 82 and the calculated heading is output at step 84. Then, the time T_0 is reset at step 86, the calculated heading reset at step 88 and the

5   process returns to step 74 to determine whether a disturbance is still occurring. If so, a new iteration of the bottom loop is performed. If not, the process leaves the bottom loop at step 76 and returns to the top of the flow chart. This embodiment can be used for different types of disturbances and different types of heading sensors.

Magnetic disturbances can be dealt with in a specific manner. The magnetic heading

10   sensor is very sensitive to magnetic disturbances that can be caused by operation of equipment on the vessel (such as electric motors, solenoids, thrusters, fish finders and pumps). The discovery of this sensitivity led to the introduction of a rate of turn sensor that is immune to the magnetic disturbances. When interference is anticipated by the method or measured by the magnetic sensor, the controller adjusts the emphasis (weighting) given any effected sensor as

15   required to minimize such magnetic disturbances. In this manner, the controller can preemptively change gains and select the proper sensor based on a priori knowledge or measurement of the disturbances caused by the use of high-EM disturbance devices.

One embodiment of this method used specifically for magnetic disturbances is shown in Fig. 5. This embodiment is similar to the flow chart in Fig. 1, but where that flow chart

20   determines whether the bow thruster is active, the present flow chart determines whether a magnetic disturbance is occurring. The heading from the heading sensor is acquired at step 90 and a heading error is calculated at step 92. The occurrence of a disturbance is determined at step 94. If no disturbance is present, the "P", "I" and "D" factors are not altered, step 96a. If a

disturbance is occurring, the "P", "I" and "D" factors are weighted differently in step 96b than in step 96a. The "D" factor is the derivative factor, proportional to a rate of change of the heading error. It is derived from the rate sensor and not from the magnetic sensor.

It has been found that the weighting for this "D" factor is desirably increased in the
5   presence of a magnetic disturbance, while the weighting for the "P" and "I" factors should be decreased since they are derived from a magnetic source. This is shown at step 96b. The Pterm, Iterm and Dterm are then calculated at step 98, the Control Out calculated at step 100 and the resulting signal is used to control the nozzle at step 102, whereupon the time is reset and a new iteration begins. When these magnetic disturbances are transient in nature, such as the activation
10   of a bucket solenoid, they primarily affect the "D" factor discussed above. In the absence of a non-magnetic rate-of-turn sensor, the weighting of this "D" factor can be lowered, and the weighting of the P and I factors raised during a disturbance. Other magnetic and non-magnetic sensors can be used and their relative weighting changed as appropriate.

In situations where the magnetic disturbance is a relatively long-term phenomenon (such
15   as a bow thruster), other terms can be effected. In these cases, when interference is anticipated or measured by the magnetic sensor in a given axis, the controller adds an offset to any effected axis as required to negate such magnetic disturbances. This offset is based on measurement of the disturbances during initial system setup. In some cases (e.g. where only one axis is affected by the disturbance) that axis is calculated from the other two axis measurements. Therefore, the
20   algorithm includes a system programmed to automatically account for any electro-magnetic disturbances.

Another embodiment is shown in Fig. 6. Here, the occurrence of a condition is assumed to create a disturbance and the heading data is corrected based on predetermined knowledge of

the effect of such a disturbance on the heading data. The magnetic X, Y and Z data are first

acquired at step 106. At step 108, it is determined whether the bucket up solenoid has been

activated. If not, the process proceeds to step 112. If so, it has been previously determined,

through testing, that a specific error is introduced into the Y axis measurement. Therefore, the Y

5   axis measurement is corrected at step 110 by adding an offset to the acquired Y axis

measurement which has previously been determined to offset the effect of the solenoid

activation. At step 112, it is determined whether the bucket down solenoid has been activated. If

not, the process proceeds to step 116. If so, the Y axis measurement is corrected at step 114.

Since the activation of the bucket down solenoid has been determined to affect the Y axis

10   measurement differently than the activation of the bucket up solenoid, a different offset is added

to the acquired Y axis measurement at step 114. At step 116, it is determined whether the bow

thruster has been activated. If not, the heading can be calculated at step 120 from the acquired X

and Z axis measurements and the Y axis measurement, whether acquired from step 106 or

corrected at steps 110 or 114. If the bow thruster has been activated, the Z axis measurement is

15   corrected at step 118 by a formula predetermined to best correct for error introduced by the

activation of the bow thruster. The heading is then calculated at step 120 with the corrected Z

axis measurement. Other disturbances can also be included in this method with corrections to the

factors being determined by previous testing, hypothesis and/or measurement.

The various embodiments disclosed herein, and various aspects of such embodiments,

20   can be combined with other embodiments and/or aspects of other embodiments to create new

embodiments. A preferred system incorporating the present invention will utilize more than one

of the disclosed embodiments.

Using Rate Of Turn To Control Roll Out

With control systems known in the field, when the operator wishes to come out of a turn, the steering command is returned to center or neutral and the nozzle automatically deflects to neutral. This results in a delayed roll out (particularly on vessels with low inertia in wind and

5   waves) and usually results in overshoot when a heading-keeping or autopilot feature is available.

In the current invention, when the operator returns the control stick (or other controller) to neutral, commanding the vessel to come out of a turn, the controller senses the vessel's rate of turn during rollout, and optionally before roll out is commenced, and the nozzle is automatically deflected proportional to the rate of turn, to oppose the turn. The nozzle position is continuously

10   updated with the rate of turn throughout the rollout. This results in a quicker, more repeatable response time to end a turn. As the vessel direction straightens (and the vessel stops turning), so does the nozzle so that the vessel and the nozzle meet at the neutral point simultaneously when the vessel completes the turn. In cases where a heading keeping feature is available, the control system then acquires the new heading. Since the vessel is not turning and the nozzle is at

15   neutral, there is no overshoot.

See Fig. 7 for a logic flow chart of this control method. To begin, the Nozzle Position Command for this control method is zero, step 130. That means that this control method is not altering the nozzle position, whether the nozzle position is neutral or turned. At step 132, it is determined whether the control stick is off-center, that is, the operator is making a turn. If not,

20   the control method returns to step 132. It should be noted, that there are different mechanical controllers for steering the vessel. This can include a joystick system where the joystick is rotated in the desired direction to steer the vessel in that direction and can also include a joystick system where the joystick is moved to the desired side (without rotation) to steer the vessel in the

desired direction. Other steering controls can also be used without altering the applicability of this control method, or other control methods discussed herein. Thus, the query as to whether the stick is off-center is merely querying whether the operator is operating the steering control, of whatever type, to steer the vessel.

5   If the stick is off center, the Nozzle Position Command is set as the Stick Position Command at step 134 so that the nozzle position is directly correlated to the stick position (ignoring adjustments to the nozzle position by other control methods). The Heading Sensor Filtering, if any, is then reduced at step 136 and it is then determined at step 138 whether the stick has returned to center or not. If not, the control method returns to step 134. If the stick is at

10   center, the Nozzle Position Command is set as the negative of the Heading Rate multiplied by a constant factor k. The Heading Rate can be determined from a calculation of the change in heading over time or can come from a Heading Rate Sensor. The constant k can be a specific constant determined for the particular vessel or can be accessed from a chart depending on other factors. It is only at step 140 that this control method actually sends a signal that is used to adjust

15   the position of the nozzle from where it would be if this control method were not in operation.

It is then again determined whether the stick is off center at step 142. If so, for instance, because the operator may be making a slight adjustment to the heading, the control method returns to step 134. If the stick is still at center, it is determined at step 144 whether the Heading Rate is less than a predetermined threshold. Below this threshold, the vessel is turning at a slow

20   enough rate to restore any filtering that was reduced in step 136.

If the Heading Rate is above the threshold, the control method returns to step 140. If the Heading Rate is below the threshold, the Heading Sensor Filters are restored at step 148 and it is determined whether the Heading Rate is below a second, lower threshold at step 152. Here, it is

being determined whether the vessel has stopped turning. Although this would indicate that the

Heading Rate should be zero, it has been found that because of noise, the Heading Rate may not

indicate zero even when the vessel is not turning. Therefore, it is determined whether the

Heading Rate is below a threshold that would allow for the noise but still be a good indicator that

5   no turning is occurring or that it is at a very low rate. If below this lower predetermined

threshold, it is assumed that the vessel has stopped turning, and the control method returns to the

top of the logic flow chart at step 130. If the Heading Rate is above the lower threshold, the

vessel may still be turning and the control method returns to step 140.

The controller can also remember the amount of nozzle trim/offset (necessary to maintain

10   a heading) in place before the operator twists the stick, and return the nozzle to that offset as the

stick is returned to neutral.

These features result in a quicker, more repeatable response time between when the

operator releases the steering device and the final heading achieved after the turn is complete,

and overshoot of the final heading is eliminated. They also result in a return to neutral that seems

15   more intuitive to the operator by compensating for factors that the operator might not have a

good feel for.

Pre-positioning Control Elements For Sideways Motion

Known waterjet control systems also have problems when initiating or stopping a

20   sideways translation. For instance, with current autopilot control systems, in both maneuvers, a

heading error must first be sensed before the autopilot can respond with a correcting nozzle angle

movement.

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For instance, when initiating a sideways movement, the bow already has significant sideways momentum by the time the autopilot-initiated nozzle movement occurs. This results in an unanticipated vessel yaw because there is sideways propulsion from the bow thruster at the bow of the vessel but no sideways propulsion yet at the stern of the vessel from the nozzle.

5   Correspondingly, when sideways movement is underway and the operator wishes to bring the vessel to a stop or change heading, a heading error must first be sensed before the autopilot can respond with a correcting nozzle movement. By the time that autopilot-initiated action occurs, the bow has slowed down significantly and the heavier stern continues moving due to significantly more sideways momentum, again resulting in vessel yaw.

10   To overcome these control problems, one aspect of the current invention uses pre-emptive, feed-forward (i.e., before heading feedback changes) algorithms that pre-position control elements in anticipation of the heading error that will develop due to the above factors. If sideways movement is being initiated, the nozzle is moved to an appropriate predetermined position that will prevent vessel yaw before heading error can occur and/or the autopilot (or other

15   heading-keeping device) senses the heading error and makes a corresponding adjustment. This repositioning of the nozzle is set to a fixed, predetermined angle based on the characteristics of the vessel and offsets the anticipated yaw. Likewise, when sideways movement is being slowed or stopped, the nozzle is moved to an appropriate predetermined position that will prevent vessel yaw before heading error can occur and/or the autopilot senses the heading error and makes a

20   corresponding adjustment. In the preferred embodiment, the heading-keeping method is used to further adjust the angle of the nozzle to account for conditions such as wind, or water current that may introduce vessel yaw.

Control parameters for these algorithms can be changed as a function of thrust, engine rpm, vessel speed, or control mode.

Time Delay Control To Minimize Vessel Twist

In a vessel with multiple propulsors, i.e., a rear nozzle, and a bow thruster, the vessel responds differently when various types of propulsors are actuated. For instance, with a vessel being propelled sideways by the rear nozzle and a bow thruster, if both propulsors are stopped,

10   the rear of the vessel would tend to drift more than the bow due to the difference in momentum caused by the lighter weight of the bow compared to the stern.   Conversely, when initiating a sideways maneuver, the rear takes more time than the bow to gain momentum.

To accommodate the different response times in a way that is unnoticeable to the operator, activation or de-activation of one or more of the propulsors that cause a fast reaction by

15   the vessel is delayed. For instance, when a sideways movement is initiated in a vessel that is heavier in the stern, activation of the bow thruster is delayed for a short time after the rear thruster is activated. This will allow the rear to gain momentum before the bow thruster is activated. The delay time is set so that that the vessel moves sideways in a very intuitive manner.

20   Similarly, when the operator wishes to end a sideways maneuver, for instance by returning the joystick to the neutral position, the controller will automatically disengage the rear thruster and wait a predetermined time period before disengaging the bow thruster to compensate for the bow slowing down more quickly than the stern. This control method eliminates the

vessel's natural tendency to yaw as a result of the difference in momentum between the bow and

the stern. The time delay can be changed as a function of thrust, engine rpm, vessel speed,

control method, size and weight distribution of the vessel or other factors.

5   Integration of Autopilot Functions Into Vessel Control System

Currently, vessels may employ an autopilot system separate from the electronic controller to

control the vessel. The present invention can integrate certain of the autopilot features into the

vessel control system by incorporating a heading sensor with the vessel control system. Use of a

conventional autopilot (and its associated hardware) is then no longer required. All controls

10   could be on one control handle, making vessel operation easier and more intuitive.

For instance, the following autopilot features can be integrated into the vessel control

system:

a. Heading keeping capability, heading setting capability and heading changing

capability.

15   b. Trim/offset necessary to maintain heading can be changed as a function of rate of

turn, duration of turn, deflection of nozzle, thrust, change in heading, etc.

c. The trim/offset in place before a sideward maneuver can be restored after the

maneuver.

d. Rudder jog capabilities that typically come with an autopilot would be

20   accomplished with the same vessel control stick.

e. Autopilot courses, waypoints, etc. can be obtained by interfacing to a separate

device, such as a GPS/Chart plotter having a graphical interface.

f. Heading keeping parameters can be optimized for the given control mode or

method. For example, the system can sense when the operator is engaging the bow

thruster at low speeds for a sideways movement, and apply the appropriate

parameters to the algorithm and filters.

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Other aspects which can be integrated into the present invention control system include:

g. Capturing heading as a function of another parameter:

i. Capture based on heading-rate for smooth, no overshoot, when coming out of

turn.

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ii. Capture based as a function of heading-rate sign change or below a threshold

for smooth, no overshoot, when coming out of turn.

iii. Capture as a function of nozzle position for smooth, no overshoot, when

coming out of turn.

iv. Capture heading based on near zero heading rate. Calculations using heading

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rate at the beginning of a roll-out can be used to display or capture the

anticipated heading the vessel will be on at the end of the turn. Heading rate

at the beginning of a roll-out can be used to compensate for a lagging heading

sensor by determining the time delay before capturing the heading.

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h. Applying nozzle, rudder as a non-linear, logarithmic or exponential function of

heading-rate (less sensitive to small changes than larger) to minimize over-working

and prolong the life of the nozzle actuator/pump/motor. This in lieu of a deadband

with a proportional term which linearly varies with rate of heading change (i.e. constant proportional gain).

i. Compensating for electro-magnetic field interference from electronics by compensating for field distortions as a function of mode or lever position, e.g. calculate z-axis magnetic field from x and y, when thruster is activated and offset y axis when bucket solenoids are energized.

j. Compensating for electro-magnetic field interference from electronics by controlling/regulating current (field is proportional to current) as a function of mode or lever position, e.g., offset y-axis when bucket solenoids are energized, offset more when high speed solenoids are energized. The current can be regulated to keep the field constant.

k. Compensating for electro-magnetic field interference from electronics by timing field measurements as a function of mode or lever position e.g. don't measure magnetic field when steering pump changing direction (large current/field transient).

l. Compensate for electro-magnetic field interference from electronics as a function of time unit is energized/de-energized (i.e. wait for field to decay before removing compensation, or even making compensation a function of time while field is decaying). This can also be used for field building-up.

m. Pulse bow thruster proportional to/as a function of stick position. Automatic pulsing of thruster or use of proportional control of motor based on lever position.

n. Adjust nozzle trim/neutral/integral/offset/bias as a function of rpm to compensate for hull dynamics/waterjet outlet. This is changing the neutral steering position as a function of rpm.

o. Determine whether vessel is planing or not, based on vessel pitch and rpm measurements. Automatically change gains according to the vessel conditions.

p. Change operator displays automatically or semi-automatically with mode of control.

These algorithms simplify vessel operation and bring operating characteristics of the vessel closer to the operator's intuition. Also, by automating certain operator functions, the vessel can be controlled more aggressively since less action by the operator is required to effect specific vessel movements. Vessel movements are smoothed by proactively controlling the nozzles based on the operator inputs and not waiting for heading errors to accumulate.

Parameters for the above algorithms (e.g. amount of deflection, constant of proportionality, etc.) can be changed as a function of thrust, engine rpm, vessel speed, control method or mode, weight and size of the vessel, shape of the vessel and other factors. Different of the embodiments can be used together in a control system and various aspects of the different embodiments can be combined in different manners to create different embodiments. The present invention also includes the apparatus with which these control methods are implemented.